Simulation of the recent multi-decadal increase of Atlantic hurricane activity using an 18-km grid regional model

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Abstract.

In this study, a new modeling framework for simulating Atlantic hurricane activity is introduced. The model is an 18-km grid non-hydrostatic regional model, run over observed specified SSTs and nudged toward observed time-varying large-scale atmospheric conditions (Atlantic domain wavenumbers 0-2) derived from NCEP Reanalyses. Using this "perfect large-scale model" approach for 26 recent August-October seasons (1980-2005), we find that the model successfully reproduces the observed multi-decadal increase in numbers of Atlantic hurricanes and several other tropical cyclone indices over this period. The correlation of simulated versus observed hurricane activity by year varies from 0.77 for hurricane counts to 0.48 for "significant" hurricane counts. For tropical storm count, accumulated cyclone energy, and TC power dissipation indices the correlation is ~0.65, and for U.S. landfalling TCs, the correlation is 0.41. The model simulates hurricanes intensities of up to category 3 (~950mb). On interannual time scales, the model reproduces the observed ENSO-Atlantic hurricane covariation reasonably well. We conclude that the model appears to be a feasible tool for exploring mechanisms of hurricane variability in the Atlantic (e.g., shear vs. potential intensity impacts). The model may potentially make useful simulations/projections of pre-1980 or 21st century Atlantic hurricane activity. However, the reliability of these projections will depend on obtaining reliable large-scale atmospheric and SST conditions from sources external to the model.

1. Introduction

Hurricane activity in the Atlantic basin has increased markedly in the years 1995 through 2005, compared with levels in the 1970s and 1980s. For example, the Accumulated Cyclone Energy (ACE) index in the Atlantic has been above normal for all of the post-1994 years except for the El Nino years of 1997 and 2002 (Trenberth 2005). The past two seasons (2004 and 2005) have been exceptional in terms of landfalling hurricane activity affecting Florida and the Gulf Coast regions compared to the average over recent decades. In this report we introduce a new regional atmospheric model designed to simulate a season of tropical cyclone (TC) activity in the Atlantic. By testing the model against observed interannual variability and trends, we hope to justify its use in probing our understanding of the factors controlling Atlantic TC activity and the implications of this understanding for predicting changes in future TC activity in the basin.

The cause of the recent upswing in activity remains unresolved, with some investigators interpreting the increase as being the latest positive phase of a multi-decadal cycle (e.g., Goldenberg et al. (2001), implying an impending return to below-normal conditions in coming decades. Bell and Chelliah (2006) view the multi-decadal fluctuations in Atlantic TC activity since the 1940s as resulting from a set of multi-decadal modes related to tropical convection, although they are not specific about the origin of these modes. Others view the changes as part of a long-term rising trend due to anthropogenically forced global warming (Emanuel (2006), Mann and Emanuel (2006), Trenberth and Shea (2006)), implying further growth of Atlantic hurricane activity in the future as a long-term climate warming trend continues in the 21st century (IPCC 2001). Determining whether the Atlantic hurricane changes in recent decades are part of a cycle, a long-term trend, or some combination of cycle and trend, is a crucial question for the future outlook of hurricane activity in the basin. It is difficult to distinguish between alternative theories for the dominant controlling factors from statistical analyses of observations alone, given the limited length of available TC activity data and concerns about reliability of historical TC data (Landsea et al. 2004; Landsea 2005; Landsea, et al. 2006).

Dynamical simulations of Atlantic TC activity potentially provide model frameworks in which the factors controlling interannual variability and trends can be analyzed more directly. The resolutions of typical global climate models are often considered inadequate for meaningful simulations of TC activity, although Vitart and Anderson (2001) simulate a decrease in Atlantic tropical storms in the 1970s and 80s, relative to the 1950s and 60s, similar to that observed, using observed SSTs. More recently, Camargo et al. (2005) have shown that interannual variability of simulated tropical storm counts and (bias adjusted) accumulated cyclone energy in the Atlantic (and other basins) was significantly correlated with observations using several low-resolution global atmospheric models forced with observed SSTs. Vitart and Stockdale (2001) and Vitart (2006) has shown that current coupled models also have skill at predicting the interannual variability of tropical storm counts a season in advance in several basins, including the Atlantic, owing in part to the skill of the models in predicting the SSTs. The focus of these studies was on tropical storms, since the resolutions of the models were inadequate to address the question of the interdecadal modulation of major hurricanes, which is so prominently seen in the observations. Concerning interdecadal variability, Vitart (2006) finds that current coupled seasonal forecast models have difficulty simulating interdecadal tropical storm variations in the Atlantic, probably due to the models' poor performance with predicting Atlantic SSTs (i.e., maintaining the interdecadal SST signals) over the 6 month integrations. Global atmospheric model simulations with ~20km grid spacing are now feasible on the largest supercomputers available (Oouchi et al. 2006), and are promising for research in this area since models of this resolution appear capable of generating storms of hurricane strength. However, these models have not yet been used to address the question of recent Atlantic interannual/interdecadal variability and trends in TC or hurricane activity.

Our choice in this work is to utilize a new high-resolution regional model covering the North Atlantic which we anticipate may be useful for addressing some of the issues surrounding tropical Atlantic hurricane variations and trends. Specifically, in this preliminary study we examine the extent to which it is possible to simulate various aspects of Atlantic tropical storm and hurricane seasonal activity using a regional climate model forced on its boundaries by the observed atmospheric state, at the lower boundary by observed SSTs, and in the interior by relaxation towards the large-scale component of the time-varying atmospheric state. This framework should be thought of as an approach towards downscaling rather than prediction. In principle, this model can be forced with global coupled model simulations to study the response of Atlantic TC activity to anthropogenic increases in greenhouse gases, for example. The relevance of this framework for seasonal prediction would clearly depend on the relative importance and predictability of the different sources of large-scale information input into the model (SSTs, boundary conditions, and large-scale interior atmospheric state). Success in downscaling historical TC activity can be thought of as a prerequisite for meaningful predictions of TC activity using a regional nested model.

Section 2 describes the basic model; section 3 contains the main results from the experiments; and section 4 contains our concluding remarks. The procedure for detecting and tracking storms and some results from preliminary exploratory and tuning experiments are presented in two appendices.

2. Model Description and Experimental Design

The atmospheric model dynamical core used for this study is the GFDL Regional Atmospheric Model (Pauluis and Garner 2006), which is compressible and nonhydrostatic. The model was run with specified observed SSTs (NCEP 1 Reanalysis, Kalnay et al. 1996) over ocean points and was coupled to the GFDL LM2 land model (based on the Land Dynamics Model of Milly and Shmakin, 2002) over land points. The land model predicts soil temperature and moisture fields and was run with five levels. The model domain covers the tropical and subtropical Atlantic, Gulf of Mexico, and parts of western Africa (see Fig. 1). The model's 690 x 300 horizontal grid has a physical spacing of 1/6 degree (~18 km) and 45 unevenly spaced vertical levels, with the lowest model level at a height of 22 m.

No cumulus parameterization is used in the primary runs. We made this choice because in preliminary experiments the model with no cumulus parameterization performed better in this context than did a model version with a particular convection scheme activated, as briefly described in Appendix B. However, Pauluis and Garner (2006) have studied the resolution-dependence of non-rotating radiative-convcective equilibrium in a doubly periodic domain with the identical model. They find some encouraging insensitivity of the largest convective cores to resolution, up to 16 km. Since radiative-convective equilibrium simulations should provide some information about the background random convective activity that generates seeds for cyclone development, these simulations encouraged us to consider the no-parameterization option.

We use the five-species cloud microphysical scheme developed by Lin (Lin et al. 1983, Lord et al. 1984), coupled to the GFDL radiation package (GAMDT 2004) assuming fixed, height-dependent cloud particle sizes. Insolation is diurnally and seasonally varying. The boundary-layer scheme is the level-2.5 turbulence closure of Mellor and Yamada (1982). Monin-Obukhov similarity theory is used for the surface flux calculations, with a ocean roughness enhancement related to windspeed according to the scheme of Beljaars (1995).

The velocity, temperature, and humidity at all levels are nudged towards the NCEP 1 Reanalysis (Kalnay et al. 1996) on a fast timescale (2 h) over a graduated five-degree-wide band around the perimeter of the domain. The target data are time-interpolated from 6-hourly reanalysis data. In addition, zonal and meridional wavenumbers 0, 1 and 2 at all levels were nudged toward the reanalysis on a slower timescale (48 h) across the entire domain. Through the nudging procedure, the model's solution is kept similar to the NCEP Reanalysis on the large-scale, while the model remains relatively unconstrained to generate smaller-scale disturbances within that solution. In that sense, we nudge toward a "perfect" large-scale solution and use the high- resolution model to provide "added value" by recovering information about smaller-scale transient disturbances, such as hurricanes, assuming that the large-scale solution is known perfectly. The utility of the spectral nudging approach for regional climate downscaling has been demonstrated previously by several investigators (e.g., von Storch et al. 2000; Weisse et al. 2005; Miguez-Macho et al. 2005; Castro et al. 2005).

The preliminary tests used to determine the nudging time scale are summarized in Appendix B. The storminess of the model is sensitive to the strength of this interior nudging, with stronger nudging reducing the number of storms. While further experiments are needed to understand this dependence, our hypothesis is that the model without nudging generates a vertical mean thermodynamic profile that is too unstable, and that one primary role of the nudging is to correct this mean profile. It is possible that without interior nudging a convective parameterization would be required, at this resolution, to prevent excessive storm development.

The experiments described here are initialized on 00Z on July 29 of each season, and integrated through the end of October. The first model data analyzed for the tropical storm detection is 6Z on July 31, allowing for about a two-day model spin-up period prior to the main analysis period. The 6-hourly output from these runs was then analyzed to objectively identify the occurrence of tropical storm and hurricane-like disturbances in the model. The storm identification and tracking procedure is presented in detail in Appendix A. We then compare the TC statistics of the model to the observed statistics (number, location, track, intensity) of Atlantic tropical cyclones as obtained from the National Hurricane Center HURDAT database (http://www.aoml.noaa.gov/hrd/hurdat/Data_Storm.html).

3. Simulation Results

a. Long-term means and aggregate storm statistics

In Fig. 1, the time-mean precipitation climatology (August-October) from the model simulations (1980-2005) is compared with the observations from the Global Precipitation Climatology Project (GPCP; http://cics.umd.edu/~yin/GPCP/main.html). Precipitation is only indirectly constrained by the interior and boundary nudging of the model, so that a comparison of simulated vs. observed precipitation is a meaningful measure of model performance. The model produces an Atlantic Intertropical Convergence Zone (ITCZ) similar in shape and magnitude to the observed ITCZ, although the model's ITCZ is slightly too confined toward the equator. The precipitation storm track along the U.S. East Coast is also well-produced in terms of position and magnitude. In the extreme eastern Pacific, the model produces substantially more rainfall than observed. The model precipitation is suppressed near the lateral boundaries in large part because of the strong nudging of the humidity towards reanalysis. This cautions against placing too much emphasis on any model features located near the domain boundaries. Other fields such as atmospheric temperatures, winds, and moisture are not compared here, as these are nudged toward the reanalysis on a 48-hr time scale on large-scales, and the climatologies remain close to the reanalyses.

Model fields for a sample hurricane from the model simulation are shown in Fig. 2. For this example, the rain rate and cloud liquid water fields from the model hurricane have features resembling rainbands surrounding the storm, and a clearly discernible eye-like feature at the storm center. The model hurricane's warm core has a maximum magnitude of over 14^{o}C at around 400 hPa. Wind speeds reach a maximum just below the 900 hPa level.

The asterisks in Fig. 1 show observed and simulated locations of all (August-October) tropical storm formations for 1980-2005. The general formation regions and densities appear to be fairly well-captured in the simulations. Figure 3 shows maps of tropical storm formation and occurrence, and of hurricane occurrence during the 26-yr simulation period. The tropical storm formation maps (a vs d) show fairly realistic simulation rates in the Atlantic Main Development Region (10^{o}-20^{o}N) and Gulf of Mexico, with excessive formation rates off the U.S. East Coast. Tropical storm occurrence rates (b vs. e) are again fairly realistic in the Main Development Region, but are somewhat too high particularly from 20^{o} to 40^{o}N. Hurricane occurrence rates are too low in the Main Development Region, and Gulf of Mexico south of 25^{o}N, but more realistic in the northern part of the domain, so that the main region of hurricane occurrence is shifted poleward in the model compared with observations.

The intensities of the simulated storms vs observations are summarized in a wind-pressure scatter plot in Fig. 4. The most intense storm simulated by the model reached a central pressure of about 947 hPa, with maximum surface winds of about 47 m s^{-1}. In comparison, observed central pressures in the Atlantic basin have reached as low as 882 hPa (Wilma, 2005), and maximum surface wind speeds as high as 85 m s^{-1} (Camille, 1969). The wind-pressure relationship in the model is substantially less linear than in the observations, as various model deficiencies act to progressively suppress wind intensities, for given central pressures, beginning at values exceeding about 25 m s^{-1}. As a result, the model simulates hurricanes into the Saffir-Simpson category 3 range in terms of central pressure (i.e., 964-945 hPa), but only into the category 2 range (43-49 m s^{-1}) in terms of maximum surface wind speed. We note that the GFDL hurricane model at similar horizontal resolution produced storms with substantially lower minimum pressures and higher near-surface wind speeds (e.g., Knutson et al. 1998) than our model used in the present study (Fig. 4). It is likely that the wind-pressure deficiency in our new model is due at least in part to the observed decrease in surface drag at high wind conditions, an effect which is being addressed in new surface flux parameterizations (e.g., Moon et al. 2006). The causes of the weak intensities produced by our model are still under investigation.

Owing to the greater model bias for wind speeds compared with central pressure, we have chosen to use central pressures where possible in assessing simulated storm intensities. For example, in determining the category of hurricane in the model, we use central pressure criteria, and for computation of the cyclone energy and power dissipation indices later in this section, we use wind speeds inferred from central pressures according to the relationship used in Landsea (1993), which is based on Kraft (1961). Furthermore, we define "significant hurricanes" in our simulations as having central pressures of 979 hPa or less (i.e., corresponding to Saffir-Simpson categories 2-5), rather than 964 hPa or less (categories 3-5) used to denote major hurricanes in observations. However, for determining whether a storm has reached tropical storm or minimal (category 1) hurricane strength, we used the original lowest model level wind speed obtained from the model without further adjustment.

b. *Interannual variability and trends in TC activity*

Time series of annual hurricane counts for observations and the simulations are shown in Fig. 5 for the 26 (Aug.-Oct.) seasons from 1980 to 2005, along with least-squares linear trend lines. A strong correspondence between the simulated and observed variability and trends is clear, with a correlation coefficient (r) of 0.77 (i.e., almost 60% of variance reproduced). Shown in Fig. 6 are similar diagrams for several other tropical storm and hurricane metrics. Tropical storm frequency (a; r=0.61), Accumulated Cyclone Energy (b; ACE, r=0.68), and the Power Dissipation Index (c; PDI, r=0.67) all show quite strong correlation between simulated and observed series. Somewhat smaller correlations are apparent for U.S. landfalling TCs (e; r=0.41) and significant hurricane counts (f; r=0.48). The simulated and observed annual mean maximum TC intensities are uncorrelated (d; r=-0.01).

These results, particularly for total hurricane counts, ACE, and PDI, indicate that the model demonstrates substantial skill in reproducing seasonal basin-wide statistics of hurricane activity provided that the large-scale environment remains close to that observed.

In terms of linear trends over the period (dashed lines), the simulated trends are in broad agreement with the observed, showing pronounced increases for all metrics except the annual mean maximum TC intensity, which increases only slightly for both the model and observations. The model underpredicts the magnitude of the observed trend in PDI (c) and U.S. landfalling TCs (e), but overpredicts the observed trend in total hurricane numbers (b). Trend magnitudes for the other metrics are rather well-simulated. The trend lines also illustrate that the model has relatively modest biases in these metrics, although it has a clear positive bias in tropical storm counts (a) and significant hurricane counts (f), and a negative bias in annual mean maximum TC intensity. With regard to the significant hurricane count bias, the use of categories 2-5 storms in the simulated count and cateogories 3-5 in the observed count contributes to the positive bias shown. Using the same categories for the simulations and observations (e.g., categories 3-5; not shown) results in the model substantially underestimating the observed number.

Two red dots appear in each diagram of Fig 6 for the year 1995. The second dot is a second ensemble member, created by beginning the integration one day earlier (i.e., July 28) than for the first ensemble member. The results for the second ensemble member are fairly similar to the first, with the greatest difference being for significant hurricane count (4 vs 7). While a large ensemble size is highly desirable, the expense of running multiple ensemble members was prohibitive in this exploratory study.

Tropical cyclone track maps for each individual year (simulated and observed) are presented in Fig. 7. The narrow lines are tracks of storms below hurricane intensity, whereas circles depict hurricane intensity, and colors of the circles depict the Saffir-Simpson category of the storm. Scanning over the results, one can readily see examples of seasons where the model has not performed well. For example, the model over-predicts activity in the El Nino year of 1997 and in 1983. The compression of tracks in the northern part of the basin in 1998 and 2004 is apparently an artifact of storms nearing the northern boundary of the model. Despite the problems, the success of the model at capturing important differences between years is encouraging. The overall character of the tracks for many individual seasons is fairly well reproduced in the model. The 2004 and 2005 seasons are unusually active in the model, as observed, with the highest two simulated ACE values being for those two years. (In observations, the ACE index for 1995 (August-October) exceeded that for 2004 and 2005, and is somewhat under-predicted by the model.) The model clearly simulates a more active basin-wide tropical cyclone regime in years 1995 and later as compared to the pre-1995 period, consistent with the results shown earlier for Fig. 6.

On the sub-basin scale, a notable shortcoming is the failure of the model to reproduce the unusually high activity observed for Florida in 2004 and the Gulf of Mexico in 2005. As noted earlier, the model has comparatively less skill at simulating the past record of U.S. landfalling TCs than basin-wide TC activity (Fig. 6 e). Whether this relative lack of skill for smaller-scale (but economically important) features, in a model that demonstrates skill on the basin-wide level, is due to model deficiencies or to the inherent stochastic nature of events on this scale is unclear.

The response of the model's Atlantic TC frequency to ENSO is examined in Fig. 8. As observed during the analysis period, fewer tropical storms and hurricanes formed during El Nino years. The percentage reduction during El Nino years is greater in the observations than in the model, particularly for hurricanes. The model simulates slightly more tropical storms during La Nina years than during neutral years, and almost the same number of hurricanes in La Nina years compared with neutral years, in both cases in broad agreement with observations. Thus, the model successfully simulates the observed aggregate ENSO-related variations of tropical storm and hurricane frequency for the study period.

4. Discussion

The results in Section 3 indicate that our regional model, with specified SSTs and nudging toward the observed large-scale atmospheric conditions, reproduces the secular increase in Atlantic hurricane activity during 1980-2005. It also captures aspects of the higher-frequency interannual variability, such as the relation of Atlantic tropical storm and hurricane counts to ENSO.

These results raise several important questions. Through what mechanisms does the model derive its simulation skill? In particular, what mechanisms are most important in the model for producing the observed trend to higher Atlantic TC activity in recent years ?

As briefly described in the Introduction, it is difficult to address this issue with statistical analyses of observations alone. Both dynamical (e.g. vertical shear, Goldenberg et al. 2001) and thermodynamical (e.g., potential intensity and SST, Emanuel 2005, 2006) measures are well-correlated with the trends and variations in TC activity, and in fact these environmental measures also tend to be well-correlated with each other. Much longer records of Atlantic TC activity would be invaluable for this purpose. For example, Mann and Emanuel's (2006) finding of a century-scale rising trend in Atlantic TC counts, similar to the warming trend in SSTs in the basin, could be an important indication that Atlantic TC activity is increasing due to greenhouse gas-induced warming. However, the reliability of basin-wide Atlantic TC statistics prior to the 1940s is a matter of contention (e.g., Landsea 2005; Landsea personal communication 2006). Moreover, the lack of reliable records of vertical wind shear and atmospheric lapse rates extending back over the entire 20th century hinders assessment of their relative roles in any such century-scale changes.

The TC regional modeling framework introduced here may provide another means of addressing these important questions. It should be possible to determine the relative importance of changes in vertical shear and in the mean thermodynamic profile for the model results. As a next step, we need to assess whether realistic simulations of Atlantic TC activity can be produced by embedding our regional model within a global atmospheric model running over observed SSTs. To the extent that this is successful, one could explore how Atlantic TC behavior is affected by very broad scale SST warming (essentially uniform through the tropics and subtropics) versus how it is affected by more localized Atlantic SST warming, such as that believed to occur during transitions to the warm phase of the AMO or in response to a reduction in aerosol forcing over the Atlantic.

5. Conclusions

We have simulated 26 Atlantic hurricane seasons (August-October) using a new regional nested model, which is forced on the boundaries and nudged on the largest spatial scales towards NCEP Reanalysis. This model demonstrates an ability to produce basin-wide hurricane statistics such as hurricane counts, ACE, and PDI that agree quite well with observed variations, including the trend toward increasing activity over the period 1980-2005. In addition, observed statistical relations of Atlantic tropical storm and hurricane frequency versus ENSO are well captured in the model. We conclude that this model demonstrates significant skill in simulating such hurricane-related statistics—provided that sufficiently reliable large-scale atmospheric conditions are available for nudging the model on large scales. Within this constrained large-scale framework, the model generates smaller-scale transients, including tropical storms and hurricanes up to category 3, having several basin-wide statistical properties similar to observed.

Some of the sub-regional details and even the basin-wide storm behavior for some seasons have clear shortcomings. For example, the model's overall tropical storm frequency is too high, especially in subtropical latitudes. The current model lacks the capability of producing higher intensity hurricanes (category 4-5), even in terms of central pressures, and the model's wind-pressure relationship is deficient at lower central pressures.

Regarding our experimental design, a single-member ensemble generally does not allow a season-by-season assessment of potential predictability, as in Vitart et al. (1997). However, by simulating 26 separate seasons, we have obtained a large enough sample for a preliminary assessment of our model's overall capability for recovering basin-wide statistics on hurricanes and tropical storms, assuming the large-scale state is perfectly known.

There are a number of potentially useful applications of this framework, to be explored in future work. For example, the model may be used to assess the relative roles of dynamical and thermodynamical factors in the recent increase of Atlantic hurricane activity. We might also attempt simulations of pre-1980 TC activity in various regions, to see whether the reported century-scale rising trend in Atlantic TC counts (Mann and Emanuel 2006) can be reproduced in a model simulation. This model might be useful in the case of the tropical Northwest Pacific, where there appear to be significant discrepancies between different assessments of TC-related trends since the mid-1960s (e.g., Emanuel 2005a; Knaff and Sampson 2006). The potential impact of greenhouse gas-induced climate warming on future hurricane activity is another area to be explored. The reliability of future projections or retrospective simulations of past TC activity will depend crucially on obtaining reliable large-scale atmospheric and SST conditions from sources external to this model.

Appendix A. Tropical cyclone detection and tracking algorithm.

The following algorithm was used to objectively identify the occurrence of tropical storm and hurricane-like disturbances in the model. The scheme is adapted from earlier work by Vitart et al. (1997) and Vitart et al. (2003) with some modifications for use with our higher-resolution, higher frequency model data.

a. Potential storm identification

Using 6 hourly data, points in space and time satisfying the following conditions are located:

1) A local relative vorticity maximum at 850 hPa exceeding $1.6e^{-4}$ s^{-1}.

2) The surface pressure must increase by at least 4 hPa from the storm center within a radius of 5 degrees. The closest local minimum in sea level pressure, within a distance of 2 degrees latitude or longitude from the vorticity maximum, is defined as the center of the storm.

3) The distance of the warm core center from the storm center must not exceed 2 degrees. The temperature must decrease by at least 0.8^{o} C in all directions from the warm core center within a distance of 5 degrees. The closest local maximum in temperature averaged between 300 and 500 hPa is defined as the center of the warm core..

Maxima and minima are located, and gradients evaluated using bicubic splines, which provide for higher precision than the model resolution.

b. Storm tracking:

After a database of potential storm snapshots satisfying the above conditions is created, a trajectory analysis is performed to link these together using the following procedure:

1) For each storm snapshot, a check is performed to see if there are storms during the following six-hour time period within a distance of 400 km.

2) If there are none, the trajectory is considered to have stopped. If there are some, the closest storm is chosen as belonging to the same trajectory as the initial storm. If there is more than one possibility, preference is given to storms which are to the west and poleward of the current location.

3) To qualify as a model storm trajectory, a trajectory must last at least 2 days, and have a maximum surface (lowest model level) wind velocity within an 8 degree radius circle centered on the storm center greater than 17 m s^{-1} during at least 2 days (not necessarily consecutive).

Appendix B. Model tuning and preliminary/auxiliary experiments.

Our experimental design was adopted based on a number of preliminary experiments, which are described briefly in this section.

Due to the large computational expense of running all 26 seasons, the full set of runs were completed only for the model with the "final settings" as discussed below. For the preliminary experiments described here, generally only one (1995) or two (1995 and 1982) seasons were run. This approach was chosen so that highly active (1995) and very inactive (1982) Atlantic hurricane seasons could be compared and to indicate whether the model was reasonably simulating both the average level of TC activity and some important aspects of its interannual variability.

The results for the preliminary experiments are summarized in Table Appen_B in terms of seasonal tropical storm counts. In the experiments with no interior (spectral) nudging, the model produces too many tropical storms. There is also evidence for too little contrast between the active and inactive seasons (1982 and 1995). A set of auxiliary experiments was done using a cumulus convection parameterization--the Relaxed Arakawa-Schubert (RAS) scheme (Moorthi and Suarez, 1992), using settings similar to those for the GFDL AM2 global model (GAMDT 2004). In the RAS experiments, the mean level of TC activity in our model is fairly realistic, without interior nudging, but there is too little contrast between the active and inactive seasons. Without cumulus parameterization, but with interior (spectral) nudging of large-scale winds, temperature, and moisture applied at all levels using a 2-hour time scale, a strong contrast between the 1982 and 1995 seasonal counts emerges, but there is too little storm activity overall. This is slightly improved upon in a 12-hour nudging run, where there is a better relative contrast between the 1982 and 1995 seasons, but still too little activity overall. With nudging (12-hour) of winds only, the model reverts to a much too active tropical storm regime with little contrast evident between the 1982 and 1995 seasons. We note, in passing, the preliminary suggestion based on this experiment that the forcing of interior circulation features is of less importance to our results than the forcing of the mean thermodynamic state. The final settings, used for our primary experiments, consists of 48-hour interior (spectral) nudging of winds, temperature, and moisture at all levels, and yields a fairly realistic contrast between 1982 and 1995, with a fairly realistic mean level of TS counts for those years.

These preliminary experiments demonstrate that the model's TC activity is sensitive to the details of the large-scale interior nudging, including what variables are nudged, and the time scale of the nudging. The final settings chosen, based on the model's performance as shown in the table, could likely be further improved upon with additional tuning. There are also likely to be other sensitivities, such as the vertical structure of the nudging, the number of horizontal wavenumbers included in the nudging, the model parameterizations, etc., but these were not analyzed for the present study.

After completing the primary series of model runs for this study, we discovered a code error in the spectral nudging routine that affected the target fields below about 1000m above sea level. The error resulted in target surface fields for the interior spectral nudging being generally too warm and moist. We re-ran the 1982 and 1995 years with this error fixed and found that the tropical storm counts reproduce the observed most closely provided that the nudging timescale is decreased slightly from 48 hours to 24 or 36 hours (Table Appen_B). We chose not to re-run our entire primary experiment (26 seasons) with this fix due to the large computational expense (~10^6 CPU hours) and apparent limited impact of the code error in the context of the present study. Results with the corrected model will be presented in due course.

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REFERENCES

Beljaars, A. C. M., 1995: The parameterization of surface-fluxes in large-scale models under free convection. *Quart. J. Roy. Meteor. Soc.*, **121**, 255-270.

Bell, G. D., and M. Chelliah, 2006: Leading tropical modes associated with interannual and multidecadal fluctuations in North Atlantic hurricane activity. *J. Climate*, **19**, 590-612.

Bengtsson, L., K. Hodges, and E. Roeckner, 2006: Storm tracks and climate change. *J. Climate*, in press.

Bister, M., and K. A. Emanuel, 1998: Dissipative heating and hurricane intensity. *Meteor. Atm. Phys*., **52,** 233-240.

Camargo, S., A. G. Barnston, and S. E. Zebiak, 2005: A statistical assessment of tropical cyclone activity in atmospheric general circulation models. *Tellus* **57A:** 589-604, DOI: 10.1111/j.1600-0870.2005.00117.

Castro, C. L., R. A. Pielke Sr., and G. Leoncini, 2005: Dynamical downscaling: assessment of value retained and added using the Regional Atmospheric Modeling System (RAMS). *J. Geophys. Res.*, **110,** D05108, doi:10.1029/2004JD004721.

Elsner, J.B., K-b. Liu, and B. L. Kocher, 2000. Spatial variations in major U.S. hurricane activity: Statistics and a physical mechanism. *J. Climate*, **13,** 2293-2305.

Elsner, J. B., R. J. Murnane, and T. H. Jagger, 2006: Forecasting U.S. hurricanes 6 months in advance. Geophys. Res. Lett., accepted for publication. Available online at: http://garnet.acns.fsu.edu/~jelsner/PDF/Research/LongLead.pdf

Emanuel, K.A., 1987: The dependence of hurricane intensity on climate. *Nature*, **326,** 483-485.

Emanuel, K. A., 1988: The maximum intensity of hurricanes. *J. Atmos. Sci.*, **45,** 1143-1155.

Emanuel, K. A., 1995: Sensitivity of tropical cyclones to surface exchange coefficients and a revised steady-state model incorporating eye dynamics. *J. Atmos. Sci.*, **52,** 3969-3976.

Emanuel, K. A., 1999: Thermodynamic control of hurricane intensity. *Nature,* **401**, 665-669.

Emanuel, K. A., 2005a: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **436,** 686-688.

Emanuel, K. A., 2005b: Emanuel replies. *Nature*, **438**, doi:10.1038/nature04427.

Emanuel, K., 2006: Environmental influences on tropical cyclone variability and trends. Proc. 27th AMS Conf. on Hurr. and Trop. Meteor., #4.2. Available online at: http://ams.confex.com/ams/pdfpapers/107575.pdf

Emanuel, K., S. Ravela, E. Vivant, and C. Risi. 2006: A statistical deterministic approach to hurricane risk assessment. *Bull. Amer. Meteor. Soc.,*: **87**, 299–314.

Enfield, D. B, and A. M. Mestas-Nuñez, 1999: Multiscale variabilities in global sea surface temperatures and their relationships with tropospheric climate patterns. *J. Climate*, **12,** 2719-2733.

GFDL Global Atmospheric Model Development Team (GAMDT), 2004: The new GFDL global atmosphere and land model AM2-LM2: Evaluation with prescribed SST simulations. *J. Climate*, **17**, 4641-4673.

Goldenberg, S. B., C. W. Landsea, A.M. Mesta-Nuñez, and W. M. Gray, 2001: The recent increase in Atlantic hurricane activity: causes and implications. *Science*, **293,** 474-479.

Gray, W. M., 1979: Hurricanes: their formation, structure, and likely role in the tropical circulation. In *Meteorology over the tropical oceans.* Ed., D. B. Shaw, Roy. Meteor. Soc., 155-218.

Gray, W. M., 1990: Strong association between West African rainfall and U.S. landfall of intense hurricanes. *Science,* **249,** 1251-1256.

Held, I. M., T. L. Delworth, J. Lu, K. L. Findell, and T. R. Knutson, 2005: Simulation of Sahel drought in the 20th and 21st centuries. *Proc. Nat. Acad. Sci.,* **102**(50), 17891-17896.

Holland, G.J., 1997: The maximum potential intensity of tropical cyclones. *J. Atmos. Sci.,* **54,** 2519-2541.

Hoyos, C. D., P. A. Agudelo, P. J. Webster, and J. A. Curry, 2006: Deconvolution of the factors contributing to the increase in global hurricane intensity. *Science*, 312: 94-97.

IPCC, 2001. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

Kalnay E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, B. Reynolds, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, R. Jenne, D. Joseph, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.,* **77,** 437-471.

Karoly, D. J., and Q. Wu, 2005: Detection of regional surface temperature trends. *J. Climate*, **18,** 4337-4343.

Knaff, J. A, and C. R. Sampson, 2006: Reanalysis of West Pacific tropical cyclone intensity 1966-1987. Proceedings of 27th AMS Conference on Hurricanes and Tropical Meteorology, #5B.5. Available online at: http://ams.confex.com/ams/pdfpapers/108298.pdf

Knutson, T. R., T. L. Delworth, K. W. Dixon, I. M. Held, J. Lu, V. Ramaswamy, D. Schwarzkopf, G. Stenchikov, and R. J. Stouffer, 2006. Assessment of twentieth-century regional surface temperature trends using the GFDL CM2 coupled models. *J. Climate,* 19(9), 1624-1651.

Knutson, T. R., and R. E. Tuleya, 2004: Impact of CO2-induced warming on simulated hurricane intensity and precipitation: sensitivity to the choice of climate model and convective parameterization. *J. Climate*, **17,** 3477-3495.

Knutson, T. R., R. E. Tuleya, and Y. Kurihara, 1998: Simulated increase of hurricane intensities in a CO2-warmed climate. *Science*, **279**(5353), 1018-1020.

Kraft, R. H., 1961: The hurricane’s central pressure and highest wind. *Mar. Wea. Log,* **5,** 155.

Landsea, C. W., 1993: A climatology of intense (or major) Atlantic hurricanes. *Mon. Wea. Rev.,* **121,** 1703-1713.

Landsea, C. W., 2005: Hurricanes and global warming. *Nature,* **438,** doi:10.1038/nature04477.

Landsea, C. W., C. Anderson, N. Charles, G. Clark, J. Dunion, J. Fernandez-Partagas, P. Hungerford, C. Neumann, and M. Zimmer, 2004: The Atlantic hurricane database re-analysis project: Documentation for the 1851-1910 alterations and additions to the HURDAT database. In: *Hurricanes and Typhoons: Past, Present and Future,* R. J. Murname and K.-B. Liu, Eds., Columbia University Press, p. 177-221.

Landsea, C. W., B. A. Harper, K. Hoarau, and J. A. Knaff, 2006: Can we detect trends in extreme tropical cyclones? *Science,* **313,** 452-454.

Lin, Y.-L., R.D. Farley, and H.D. Orville, 1983: Bulk parameterization of the snow field in a cloud model. *J. Climate Appl. Meteor.*, **22,** 1065-1092.

Lord, S. J., H. E. Willoughby, and J. M. Piotrowicz, 1984: Role of a parametrised ice-phase microphysics in an axisymmetric nonhydrostatic tropical cyclone model. *J. Atmos. Sci.*, **41,** 2836-2848.

Mann, M. and K. Emanuel, 2006: Atlantic hurricane trends linked to climate change. *EOS*, **87**, 233-241.

McDonald, R. E., D. G. Bleaken, D. R. Cresswell, V. D. Pope, and C. A. Senior, 2005: Tropical storms: representation and diagnosis in climate models and the impacts of climate change. *Clim. Dyn.,* **25:** 19-36, DOI: 10.1007/s00382-004-0491-0.

Mellor, G. L., and T. Yamada, 1982: Development of a turbulent closure model for geophysical fluid problems. *Rev. Geophys. Space Phys*. **20,** 851-875.

Michaels, P. J., P. C. Knappenberger, and R. E. Davis, 2006: Sea-surface temperatures and tropical cyclones in the Atlantic basin. *Geophys. Res. Lett*., **33**, L09708, doi:10.1029/2006GL025757.

Miguez-Macho, G., G. L. Stenchikov, and A. Robock, 2005: Regional climate simulations over North America: interaction of local processes with improved large-scale flow. *J. Climate*, **18,** 1227-1246.

Milly, P. C. D., and A. B. Shmakin, 2002: Global modeling of land water and energy balances. Part I: The land dynamics (LaD) model. *J. Hydrometeor*., **3**(3), 283-299.

Moon, I.-J., I. Ginis, T. Hara, and B. Thomas, 2006: Physics-based parameterization of air-sea momentum flux at high wind speeds and its impact on hurricane intensity predictions. *Mon. Wea. Rev.,* accepted for publication.

Moorthi, S., and M. J. Suarez, 1992: Relaxed Arakawa-Schubert: A parameterization of moist convection for general circulation models. *Mon. Wea. Rev.,* **120,** 978-1002.

Oouchi, K., J.Yoshimura, H. Yoshimura, R. Mizuta, S. Kusunoki, and A. Noda, 2006: Tropical cyclone climatology in a global-warming climate as simulated in a 20km-mesh global atmospheric model: frequency and wind intensity analysis. *J. Meteorol. Soc. Japan*, , **84**, 259-276.

Pauluis, O., and S. T. Garner. 2006: Sensitivity of radiative-convective equilibrium simulations to horizontal resolution. *J. Atmos. Sci.,* **63,** 1910-1923.

Royer. J.-F., F. Chauvin, B. Timbal, P. Araspin, and D. Grimal, 1998: A GCM study of the impact of greenhouse gas increase on the frequency of occurrence of tropical cyclones. *Clim. Change*, **38,** 307-343.

Santer, B. D., and Coauthors, 2005: Amplification of surface temperature trends and variability in the tropical atmosphere. *Science*, **309,** 1551-1556.

Saunders, M. A., and A. S. Lea, 2005: Seasonal prediction of hurricane activity reaching the coast of the United States. *Nature*, **434,** 1005-1008.

Sherwood, S. C., J. R. Lanzante, and C. L. Meyer, 2005: Radiosonde daytime biases and late-20th century warming. Science, 309, 1556-1559.

Trenberth, K., 2005: Uncertainty in hurricanes and global warming. *Science*, **308**, 1753-1754.

Trenberth, K. E., J. Fasullo, and L. Smith, 2005: Trends and variability in column-integrated atmospheric water vapor. *Clim. Dyn.,* **24:** 741-758.

Trenberth, K. E., and D. J. Shea, 2006: Atlantic hurricanes and natural variability in 2005. *Geophys. Res. Lett.*, **33,** L12704, doi:10.1029/2006GL026894.

Vitart, F., J. L. Anderson, and W. F. Stern, 1997: Simulation of inter-annual variability of tropical storm frequency in an ensemble of GCM integrations. *J. Climate*, **10**, 745-760.

Vitart, F. and J. L. Anderson, 2001: Sensitivity of Atlantic tropical storm frequency to ENSO and interdecadal variability of SSTs in an ensemble of AGCM integrations. *J. Climate*, **14**(4), 533-545.

von Storch, H., H. Langenberg and F. Feser, 2000: A spectral nudging technique for dynamical downscaling purposes. *Mon. Wea. Rev.* **128:** 3664-3673.

Walsh, K. J. E., K.-C. Nguyen, and J. L. McGregor, 2004: Fine-resolution regional climate model simulations of the impact of climate change on tropical cyclones near Australia. *Clim. Dyn.*, **22,** 47-56, DOI: 10.1007/s00382-003-0362-0

Webster, P. J., G. J. Holland, J. A. Curry, and H.-R. Chang, 2005: Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science*, **309,** 1844-1846.

Weisse, R., H. von Storch and F. Feser, 2005: Northeast Atlantic and North Sea storminess as simulated by a regional climate model 1958-2001 and comparison with observations. *J. Climate* **18,** 465-479.

Yoshimura, J., M. Sugi and A. Noda, 2006: Influence of greenhouse warming on tropical cyclone frequency. *J. Meteor. Soc. Japan*, **84**, 405-428.

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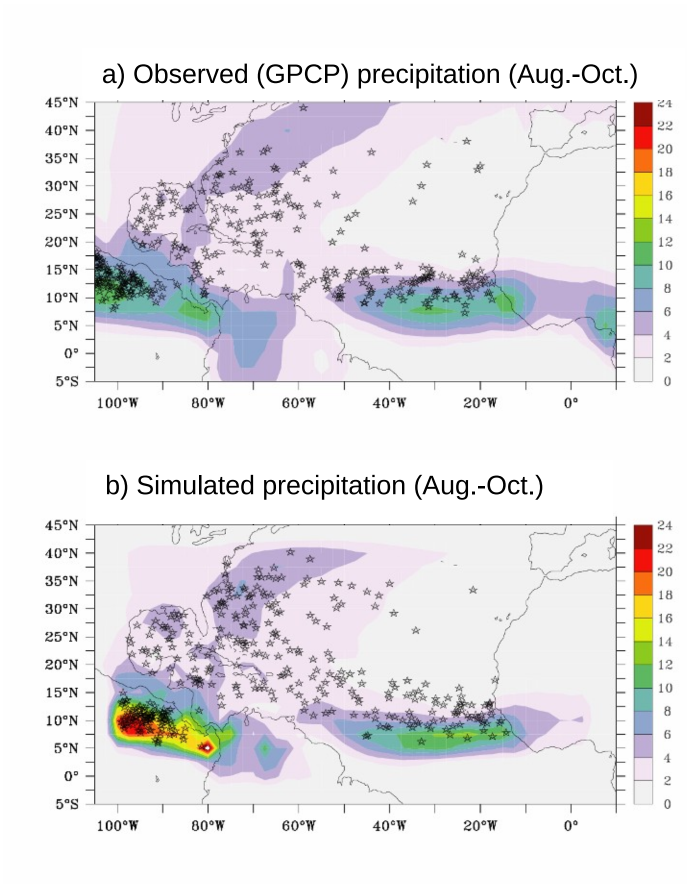

Fig. 1. Precipitation climatology (August through October) from a) observations of the GPCP and b) simulations. Units are mm day^{-1}. Observed and simulated tropical storm origin points for 1980-2005 are denoted by asterisks.

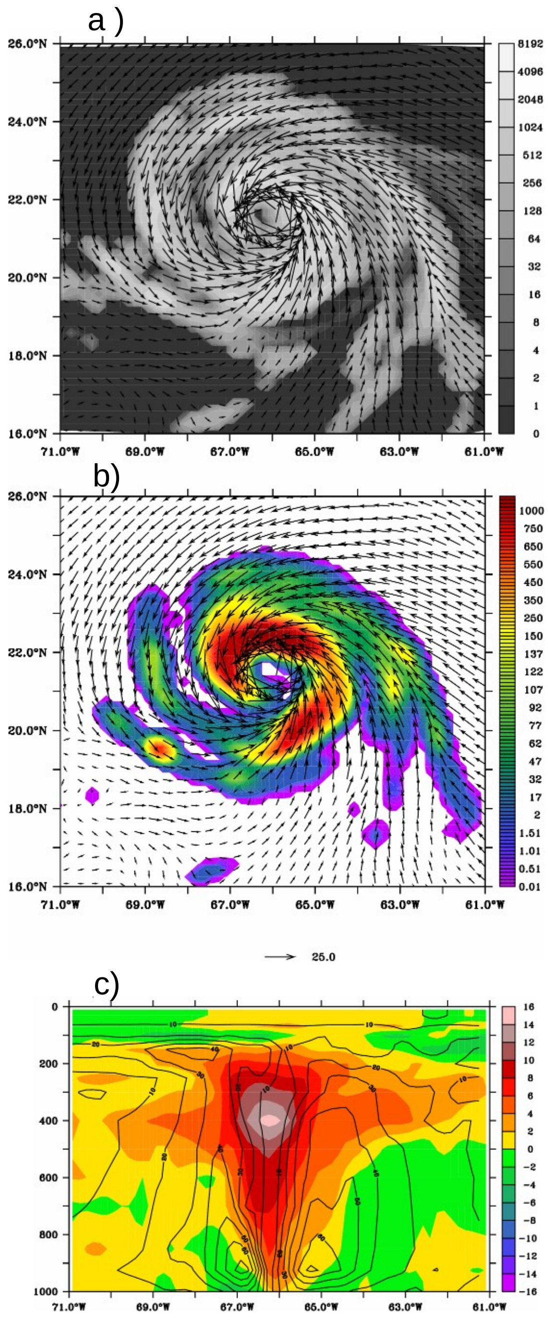

Fig. 2. Sample hurricane from the model: a) vertically integrated cloud liquid water [g m^{-3}] and surface wind vectors; b) rainfall rate in mm day^{-1} and surface wind vectors, with reference 25 m s^{-1} vector shown below diagram; and c) temperature anomaly (shading) along an E-W cross section through the storm, computed relative to the zonal mean from 79^o-69^oW and 63^o-53^oW, and wind speeds (contours).

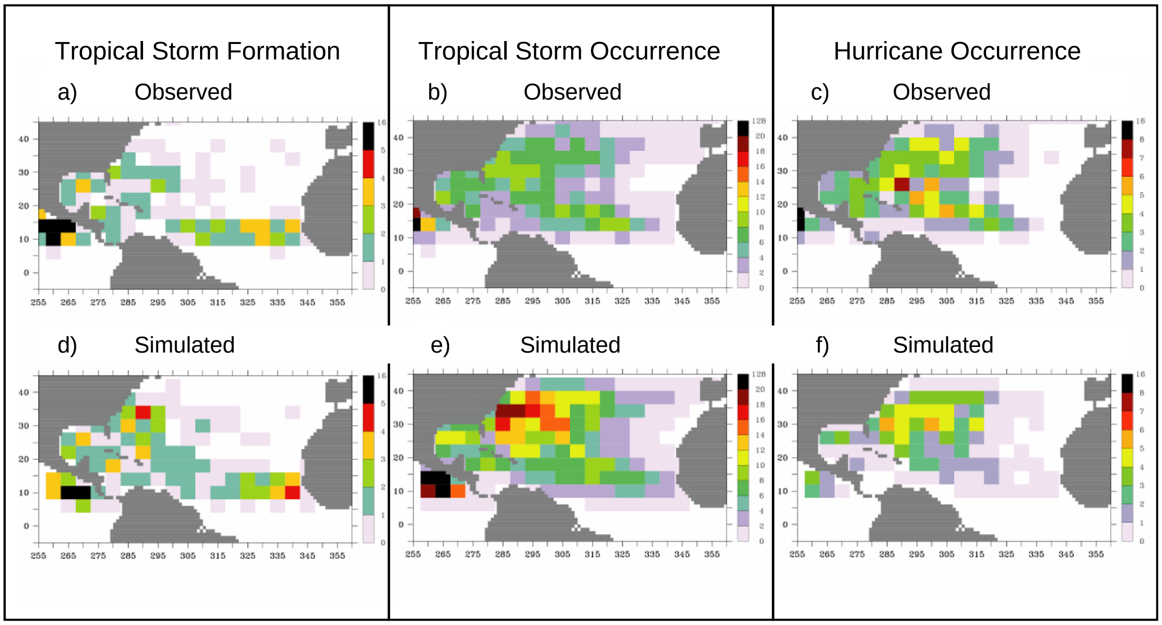

Fig. 3. Maps of observed geographical distribution of a) tropical storm formation; b) tropical storm occurrence; and c) hurricane occurrence within 4^{o} latitude x 5^{o} longitude grid boxes. Simulated distributions are in (d-f).

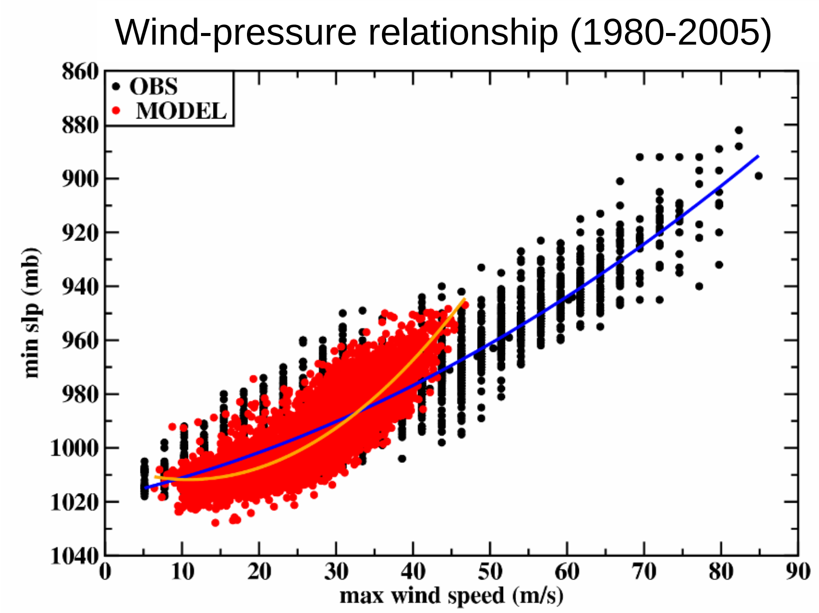

Fig. 4. Scatter plot of maximum surface wind speed versus minimum sea level pressure for observed (black) and simulated (red) Atlantic TCs (1980-2005). Units are m s^{-1} for winds and hPa (mb) for sea level pressures.

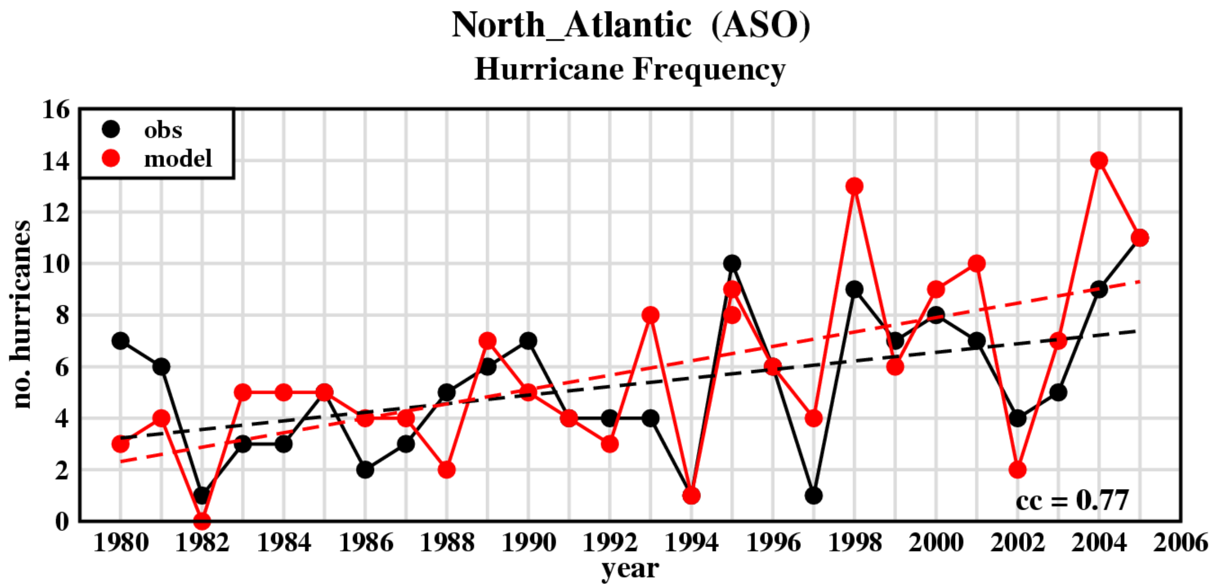

Fig. 5. Annual number or index value (August-October) of North Atlantic basin hurricanes (1980-2005). Results are shown for observations (black) and model simulations (red) for all August-October seasons. See text for description of criteria used to identify hurricanes. Least-squares best fit linear trends are depicted by the dashed lines.

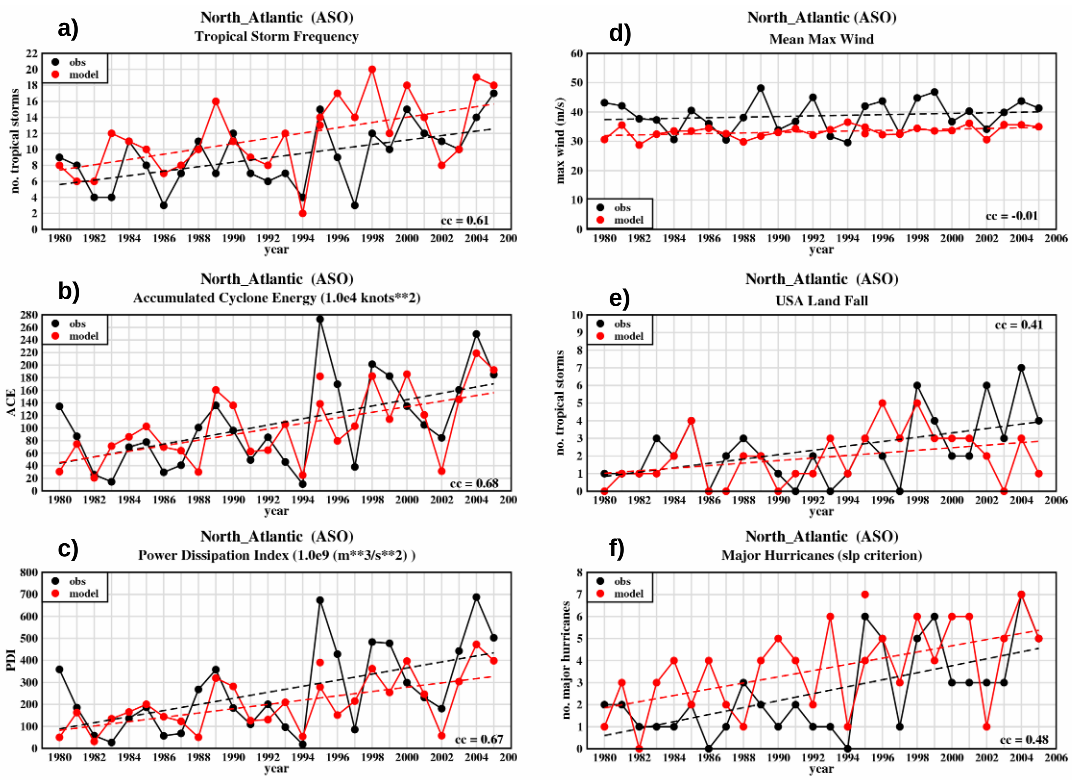

Fig. 6. Annual number or index value (August-October) of North Atlantic basin a) tropical cyclones (TCs); b) Accumulated Cyclone Energy (ACE) in units of 10^4 knots^2; c) Power Dissipation Index (PDI) in units of 10^9 m^3 s^{-2}; d) Annual mean maximum surface wind speed across all TCs in m s^{-1}; e) U.S. landfalling TCs; and f) significant hurricanes (categories 3-5 for observed; 2-5 for model). Results are shown for observations (black) and model simulations (red) for all August-October seasons from 1980-2005. See text for description of criteria used to identify TCs and hurricanes. Least-squares best fit linear trends are depicted by the dashed lines in each diagram.

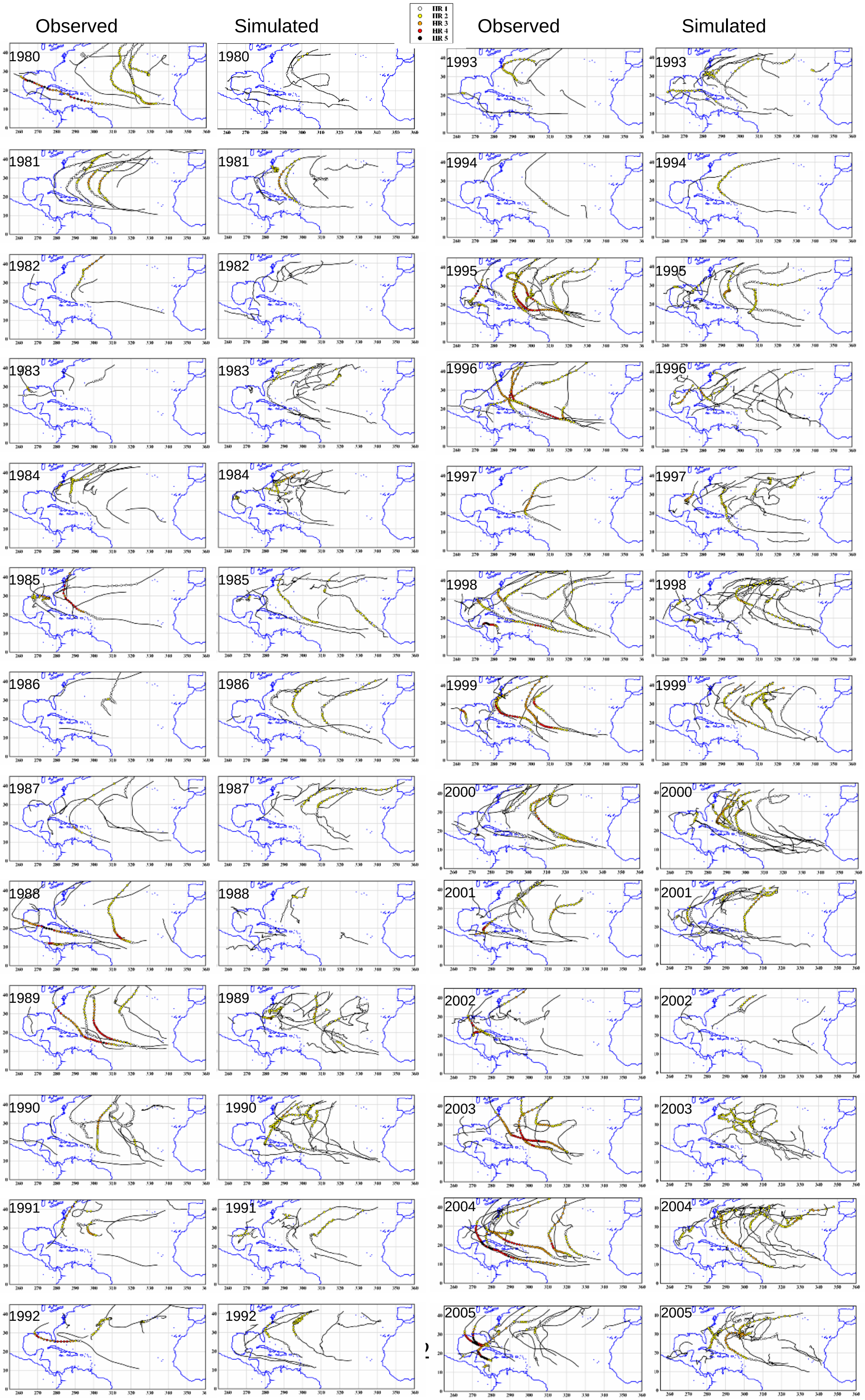
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Fig. 7. Tropical cyclone tracks for observations and simulations (Aug. – Oct. season, 1980-2005). Circles indicate times when storms were of at least hurricane strength; color shading in circle denotes Saffir-Simpson category intensity, based on central pressure criterion (see legend).

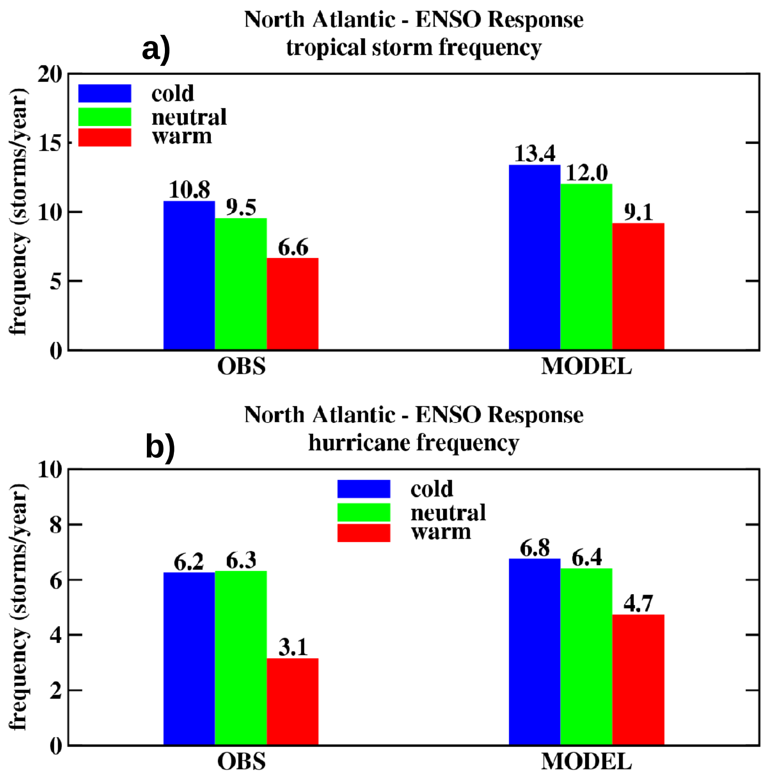

Fig. 8. Frequency of occurrence of a) tropical storms and b) hurricanes during El Niño warm events (red), ENSO neutral seasons (green), and La Niña cold events (blue). Results are shown for observations (left) and Zetac model simulations (right). El Niño years include 1982, 86, 87, 91, 94, 97, 2002, and 2004. La Niña years include 1983, 84, 85, 88, 95, 98, 99, and 2000. Remaining years are "Neutral". Year classification from: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml.

Table 1. Preliminary and auxiliary model experiments for August-October 1982 and 1995.

Model version	**1982 Tropical storm count**	**1995 Tropical storm count**
Observed	4	15
No nudging	18	25
No nudging, RAS convection	8	12,11
2-hour nudging	1	10
12-hour nudging	3	10
12-hour nudging – winds only	9[#]	9[@]
48-hour nudging (PRIMARY MODEL)	6	14,13
48-hour nudging (with error corrected in nudging code)	10	21
36-hour nudging (with error corrected in nudging code)	4	16
24-hour nudging (with error corrected in nudging code)	4	16

Run through Sept. 1 only.
@ Run through Aug. 25 only.